Plasma Sheet and Ring Current Formation from Solar and Polar Wind Sources

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Abstract

We consider the formation of the plasma sheet and quiet ring current in the framework of collisionless test particle motions in 3D magnetospheric fields obtained from self-consistent MHD simulations. Simulation results are compared with observations of the near-Earth plasma sheet from the Polar spacecraft, during 2001 and 2002. Many particles were initiated in two regions representative of the solar wind source upstream of the bow shock and the polar wind source outside the plasmasphere, both of which are dominated by protons (H^+). Variable and localized ionospheric O^+ outflows are deferred to a future study in favor of the more pervasive light ion polar wind outflows. Proton trajectories are run until they precipitate into the atmosphere, escape from the simulation space, or become stably trapped. These calculations produce a database of proton characteristics in each 1 R_E^3 volume element of the magnetosphere, and yield velocity distributions where sufficient numbers of particles pass through a volume. We report results reflecting steady growth phase conditions after 45 minutes of southward interplanetary field, Bz = -5 nT (By=0), and for conditions resulting after two hours of northward Bz = +5 nT (By=0). The results exhibit structuring of the magnetospheric plasmas according to source region, with mixed regions as well. The simulated velocity distributions are consistent with the Polar soundings of the current sheet from lobe to lobe, and with AMPTE/CCE observations of ring current protons. The simulations help us affirm the differentiation between solar and polar wind H^+ ions in the observations. The weak NBz ring current pressure is dominated by polar wind protons, while the moderately active SBz ring current pressure is dominated by solar wind protons. The solar and polar wind contributions to the SBz ring current are comparable in density, but the solar protons have a higher average energy. Solar wind protons are found to enter the ring current region predominantly via the cusp and-or dawn flank, bypassing the midnight plasma sheet, while polar wind protons enter the ring current through the midnight plasma sheet. The most important conclusion of this study appears to be that solar wind and ionospheric plasmas take such different transport paths to the ring current region. Accordingly, they should be expected to respond differently to substorm dynamics of the magnetotail, as observed recently by remote neutral atom imaging from the IMAGE mission.

Introduction

Since the definitive observation of geogenic (O^+) ions in the magnetosphere [Shelley et al., 1973], it has been known that ionospheric cold plasmas contribute to the hot plasmas of the magnetosphere. But it was also observed that heavy ions are an important constituent during times of magnetospheric storms, when there is substantial dissipation of energy in the ionosphere proper, below a few thousand km altitude [Peterson et al., 1981, 1982; Sharp et al., 1985; Hamilton et al., 1988; Daglis et al., 1999]. Observations have gradually revealed that energy dissipated in the ionosphere goes partly into energization of heavy ions sufficient to overcome their gravitational binding to the Earth [Sharp et al., 1976; Klumpar et al., 1979]. A review of the ionospheric supply of magnetospheric plasma sources was given by Moore et al., [1999a]. More recent trajectory work by Cully et al. [2003] shows that the ionospheric supply of plasma to the plasma sheet, especially heavy O^+ plasma, is not only important but is strongly modulated by convection as driven by the interplanetary magnetic field.

The ionosphere has been known to supply cold light ion plasma to the magnetosphere since the discovery of the plasmasphere [e.g., Freeman et al., 1977]. On openly convecting field lines, polar wind occurs continuously as convection opens the field lines and empties their accumulations into the polar lobes and downstream solar wind, so that they never reach equilibrium pressures. Plasmapheric plasmas result from polar wind-like light ion outflows into the nearly co-rotating inner magnetosphere, where they are trapped and accumulate to equilibrium pressures, and are therefore called “refilling flows.” Recently, the outer plasmasphere has been shown to flow sunward during magnetospheric disturbances [Elphic et al., 1997; Sandel et al., 2001; Goldstein et al., 2002], and these cold plasmas have been discovered to be present in the subsolar low latitude magnetopause region under a wide variety of conditions [Su et al., 2000; 2001; Chandler and Moore, 2003; Chen and Moore, 2004]. When strong convection drains away part of the plasmasphere, the supply of plasma is enhanced in a transient way by the rapid release of accumulated plasma. Under steady conditions, however, the plasmasphere remains trapped and the magnetosphere is supplied only from the higher latitude regions.

Nevertheless, the contribution of ionospheric light ions to magnetospheric hot plasmas is less well established and is complicated by the difficulty of discriminating protons of solar or geogenic origin. Christon et al. [1994] used energy spectral features, in comparison with He^{++} assumed to be of solar origin, to estimate the relative contributions. They found that both solar wind and polar wind contributed comparable densities to the hot magnetospheric plasmas, with a somewhat lower ionospheric contribution for high solar activity levels.

In this paper we simulate the light ion polar wind outflows that are pervasive, continuous, and at most weakly responsive to solar wind intensity or magnetospheric activity. We also simulate the entry of solar wind plasmas into the magnetosphere under the same conditions. We consider extreme conditions of purely southward and purely northward IMF, deferring consideration of more typical “Parker spiral” IMF with By dominant. We also defer consideration of auroral zone acceleration of ionospheric ion outflows, including heavy ion outflows (predominantly but not exclusively O^+) associated with electromagnetic and kinetic energy dissipation within the ionosphere proper. The light ion auroral outflows have fluxes similar to polar wind, while the heavy ion outflows have fluxes that range from much less than to much greater than polar wind outflows depending on the free energy available [Moore et al., 1999b]. Using these simulations, we address the question of how solar and polar wind protons are distributed in the magnetosphere over the full range of interplanetary conditions.

Observations

We begin by presenting relevant observations from the Polar spacecraft, the orbital apogee of which reached to the equatorial plasma sheet and swung through the midnight region during the Fall of 2001, and 2002. The plasma sheet is highly dynamic on time scales that cannot be sampled continuously using the 18 hour orbit of Polar. However, during slow apogee passes through the plasma sheet, a dichotomy is observed between quiet periods when the current sheet is a few Re thick (reversal of Bx), and active periods when the current sheet is much thinner with a thickness of only a few tenths of an R_E. During such active periods, individual or multiple substorm dipolarizations are observed, with associated strong plasma flow features. Kletzing et al., [1999] have previously reported on the characteristics of the electron plasma sheet, while TIMAS observations of the more energetic ion plasma sheet have been reported, e.g. by Cattell et al. [1999]. Baker et al. [2002] have reported a multi-spacecraft event study of substorm dipolarization events in the plasma sheet. Nakamura et al., [2002] explore the characteristics of near-Earth substorm events as observed in the plasma sheet. In the present paper, we focus instead on the steady structure of this region and the ion velocity distributions that define that structure in relatively quiet times, but we also point toward variations that would be expected in more active periods.

Figure 1 illustrates typical characteristics of the plasma sheet as seen by the Polar TIDE investigation [Moore et al., 1995], sampling energy from 0.3 eV to 450 eV, over the full range of spin angle around the orbit-normal spin axis of Polar. A pervasive feature of the magnetospheric lobe regions away from the current sheet is a cold "lobal wind". The term "lobal" is used here to apply to any high thermal Mach number plasma flows through the lobes, while "polar wind" is reserved for cold light ion outflows containing little if any O+ outflows, which must originate from auroral processes, and are therefore a subset of lobal winds. Thus, lobal winds must originate in the high latitude ionosphere, but may represent a mix of classical light ion polar wind and warmer components originating from the auroral zones or polar cap auroral features. These may contain a substantial or even dominant heavy ion component. Often, multiple species can be observed in the energy/charge distribution as multiple peaks [Moore et al., 1997].

Figure 1. Polar/TIDE observations of the plasma sheet are plotted for an orbit on 21 Oct 2001, illustrating the following features: a) lobal wind in both hemispheres, b) bidirectional streaming in the plasma sheet boundary layer, c) nearly isotropic warm plasma in the current sheet region, d) localized auroral acceleration and heating of the lobal wind outflows.

Figure 1 also illustrates the typical formation of bidirectional streaming in the low energy ions near but not at the magnetic current sheet. Such bidirectional streams are often asymmetric in temperature or Mach number, the beam traveling away from the plasma sheet being substantially warmer than the beam traveling toward the plasma sheet. Finally, Figure 1 illustrates the isotropization in angle and extension in energy beyond the TIDE range, which is typical in the plasma sheet in the vicinity of the current sheet. Figure 2 shows an example of the higher energy range ions and electrons associated with these current sheet crossings, from the TIMAS and

Hydra investigations. These have characteristic energies much higher than can be observed by TIDE, but are limited to the regions near the current sheet.

Figure 2. TIMAS and Hydra observations of hot plasma ions and electrons illustrating the full thermal extent of the hot isotropic current sheet plasmas.

In addition to the features described above, an additional pervasive feature of the Polar observations in this region is a region of hot and therefore low Mach number flow of ions, embedded within the colder lobal wind outflows from the ionosphere. These are identified as nightside auroral zone ion outflows of either the beam or conic varieties. These appear with more or less prominence, presumably dependent upon the conjugate auroral activity on the flux tubes in which they appear. They are of higher parallel and perpendicular energy, with a broader angular pattern than the relatively cold lobal wind flows. While the range of energies is continuous, such auroral outflows are easily distinguished from the lobal wind flows within which they are usually embedded.

In Figure 3, we summarize these observations schematically, showing the various velocity distribution types in their typical arrangement along a Polar orbit, relative to the current sheet, plasma sheet, and lobes. It can be seen that the plasma sheet appears as a layered structure of velocity distribution features, as described above. While there is considerable variability in the extent and prominence of the various features from pass to pass, presumably associated with substorm activity, a substantial repeatability of this pattern is observed over many passes through the region, and it can be considered to be an underlying structure, upon which variations are superposed. In the following sections, we investigate the degree to which this structure can be understood in terms of the particle populations that enter and travel through the plasma sheet region.

Figure 3. A schematic collage of the various velocity distribution types and their association with observing position relative to the current sheet, along a typical Polar Orbit.

Modeling

For this study, M-C Fok implemented a 3D full particle motion calculation in fields that are specified on a regular spatial grid of points. This calculation is based on the full particle simulation of Delcourt et al. [1993]. In past use of this trajectory code, fields have usually been specified by empirical models that can be evaluated continuously at any point in space. The magnetic field is usually given by the Tsyganenko [1989] model (more recent empirical field models are more realistic but also more computation-intensive), while the electric field or plasma flow is given by an empirical model of ionospheric convection, mapped along the T89 field lines to arbitrary points in space, assuming equipotential magnetic lines of force. Several different electric field models have been considered, for example the simple Stern-Volland model [Stern, 1975; Volland, 1978], or the more strongly-featured Weimer [1995] model.

However, in the present calculation, these empirical model fields are replaced by the self-consistently computed fields from the magnetohydrodynamic simulation of Lyon, Fedder, and Mobarry [Fedder et al., 1995; Mobarry et al., 1996]. For computational efficiency, we resampled the LFM fields onto a spherical grid with polar axis aligned to the GSM-X axis. The spacing in polar angle is a uniform 2° and the resolution in azimuthal angle on the GSM XY plane is ~5.5 deg. The grid spacing in radius varies with polar and azimuth angles with higher spatial resolution on the dayside and lower on the nightside. This approach allows very rapid identification of the current cell in which a particle is positioned, as it moves.

Integrating particle trajectories requires a method for interpolating between the grid points of the MHD simulation to enable calculation of field values at any point, as a particle moves about within the simulation space. A number of technical issues arise in performing this interpolation. For example, it can be shown that a simple linear interpolation in 3D is the only procedure that preserves the divergence free requirement on the magnetic field components. Therefore, we use here a simple linear interpolation in place of more sophisticated techniques that would allow continuous field gradients at the grid points. The inevitable field gradient discontinuities at grid points are a source of numerical diffusion, increasing with the coarseness of the grid used.

For time stepping, our approach is to step the particles a large number of times per gyro period, typically 72 times or every 5 deg. of gyrophase, using Delcourt's double precision implementation of a 4th order Runge-Kutta algorithm. This is more accurate than required for the trajectory durations we use. We have previously shown [Moore et al., 1999], that the trajectories are precisely reversible over flight paths of many 10s of R_E, and many hours (when used with analytically continuous fields).

To test the performance of the finite element interpolation approach used here, we resampled the analytically continuous (T98-Stern-Volland) field models onto our magnetohydrodynamic field grid, and compared typical trajectories with the same initial conditions. We found that the results were indeed sensitive to grid spacing, indicating numerical errors. To minimize such effects, we used the finest practical grid spacing for our MHD simulation fields, and determined that the numerical effects were substantially reduced. The main effect of such errors is a diffusive effect on the particle trajectories.

Table 1. Source region particle initial conditions

Parameter	Value	Comment
Solar Wind		
Density	6.5 cm-3	typical
Thermal speed (Temp)	31 km/s (kT=5eV)	"
Velocity	400 km/s	"
Mean PSD	2×10^{11}	
Polar Wind		
Density	0.5 cm-3	Su et al. 1998
Thermal speed (Temp)	17 km/s (1.5eV)	"
Velocity	100 km/s	"
Mean PSD	2×10^{11}	"

The present simulation study was set up by considering both solar wind and polar wind particle populations. For the solar wind, initial positions were randomly selected from a uniform distribution over a GSM yz plane at x = 15 R_E, upstream of the simulated bow shock. For the polar wind, we started protons at 4 R_E altitude with invariant latitudes uniformly distributed above 55˚ and over all local times. Auroral acceleration processes have not been applied to polar wind originating in that region, but the total escaping flux of protons is relatively unaffected by such processes [Moore et al., 1999]. Initial velocities were selected randomly from a uniform distribution of width equal to the specified thermal speed, as shown in Table 1. Particles were run until they precipitate into the atmosphere, escape from the simulation volume, or exceed a time limit of 10 hours, indicated that the protons have become stably trapped in the ring current region.

A large number of particle trajectories was run and accumulated into a spatial database of bins with resolution of 1 R_E^3, for both solar wind and polar wind particles. The record for each particle consists of one line describing the particle initial conditions, and many lines describing the particle state as it crosses each boundary in physical space. In general, particles were run with randomly selected initial conditions (within specified ranges) until the most populated bins contained >1000 particles. Some bins tend to remain empty, particularly for solar particles, because most of them pass through the system without entering the magnetosphere. To counter this, additional solar particles were run, focusing on the upstream regions with high probability of entry, until the most populated inner magnetosphere bins contained >100 solar particles. Requiring 100 particles in each bin provides reasonable granularity for assessing the dominant transport paths, the qualitative particle velocity distribution, and for estimation of bulk properties of the plasma.

Bulk properties were estimated following an extension of the method described by Chappell et al. [1987] and Delcourt et al., [1989]. Examples of both are exhibited in subsequent figures. For each particle in a given spatial bin, the particle velocity and transit time for that bin are calculated. To calculate density, we divided the entire simulation space into bins of 1 R_E^3 volume. For a particle (i) passing through a particular bin (j), the contribution of density in this bin by this particle is:

$$nij = Fi * Tij / Vj \quad (1)$$

where Fi is the ion source flux in ion/s for particles of the specified velocity, Tij is the residence time of particle i in bin j, and Vj is the volume of bin j, that is 1 R_E^3 in our case.

Fi is computed directly from the density and flow of the source plasma across the source boundary.

$$Fi = ns * vs * dA \;;\; dA = A/NT \quad (2)$$

Here dA is the area of the source surface allocated to each particle, which is the total area of the source divided by the number of particles emitted, assuming a uniform distribution of particle emission on the source surface, which is must be assured when randomizing the initial locations. The source number density and flow velocity may be specified, or the product of those two is just as useful, if better known.

Substituting (2) into (1), we have

nij = ns * vs * A * Tij / (Vj * NT)   (3)

The density at bin j is just the summation of nij over all particles that are passing through bin j:

nj = Summation in i (nij)   (4)

These relations can be applied to any source flowing across a boundary surface. The density from the ionospheric outflow can be calculated in a similar way. In that case, Vsw should by replaced by Vpw and other parameters are replaced with values appropriate to the polar wind.

These relations can be applied to any source flowing across a boundary surface. Once densities are calculated, pressure at bin j is given by,

Pj = Summation in i (Pij)   and

Pij = 2 * nij * Eij / 3

where Eij is the average energy of particle i in bin j.

For the solar wind case:
ns = 5 cm-3; vs = 400 km/s or 4e7 cm/s; A = 3600 R_E^2; NT = 800000

For the polar wind case:
ns * vs = 3e8 $(1.15/4)^3$ $cm^{-2}s^{-1}$ = 7.1e6 $cm^{-2}s^{-1}$; A = area of sphere 4 Re radius for invariant latitudes above 55 deg = 18.18 R_E^2; NT = 20000

This method of computing bulk properties allows for the diffusive filling of velocity space from source populations that tend to be highly structured in velocity space at any particular location [Moore et al., 1999]. If the relatively low resolution (i.e. smoothed) fields we use were realistic on all spatiotemporal scales, and there were no diffusive processes present, observed velocity distributions would be very finely structured with narrow features. In practice, magnetospheric fields include fluctuations over a wide range of frequencies, which are evidently diffusive, since extremely fine features are not observed within hot plasmas, though of course certain anisotropies are observed, as discussed above. Our bulk properties calculation attributes to each particle both a mean phase space density and a velocity space volume over which each particle is representative of the source. This allows for the particle weighting to be spread over the full region of velocity space at each location in the simulation space, rather than characterizing only a single point in velocity space.

In Figures 4 and 5, we display plots of the MHD fields, as they are specified at two points in time by the LFM MHD simulations. The simulation is for a time sequence that involves a few hours of northward Bz, an abrupt southward turning for two hours, and finally, a return to northward IMF [Slinker et al. 1995]. For the NBz case of this study, we selected a time two hours after the establishment of northward IMF, to allow stabilization under those conditions. For the SBz case, we selected a time about 45 minutes after the southward turning, well after the formation of a distant reconnection X line, but well before the appearance of a near-Earth X line and ejection of a plasmoid. That is, we chose a state representative of the substorm growth phase, when the magnetotail closely resembles a Level -2 T89 field (corresponding to Kp ~ 1-2) Earthward of the distant neutral line at ~40 R_E. This choice for the MHD field snapshot was motivated by a desire to maintain rough consistency with earlier simulations that have been done in the Stern-Volland-T89 field models, and with Polar observations of the quiet inner plasma sheet, which are best fit by a T89 activity level of 2 out of 6. For such cases, the current sheet as sampled by Polar is moderately thick, rather than being a thin sheet case typical of strong activity. In the future, we plan to perform similar studies appropriate to more dynamic thinner current sheet conditions in the inner plasma sheet.

For the SBz case of Figure 4, subsolar reconnection and distant plasma sheet reconnection are indicated by the blue “x” markings in the figure. Subsolar reconnection drives a high latitude flow that reinforces and becomes part of the double cell circulation flow in the equatorial plane, as shown in the lower panel of the figure. The magnetotail pressure distribution drives an earthward flow up to about 150 km/s in the inner plasma sheet. The action of the distant neutral line helps to inflate the plasma sheet during this period, but is being convected tailward and has little influence on driving sunward convection at this point in the growth phase.

Figure 4. The computed magnetohydrodynamic fields for the SBz case. (top) The magnetic (B) lines are indicated in the noon-midnight meridian. (bottom) The electric field is indicated as color contoured values of the Vx in the GSM-XY plane, coded to discriminate sunward (reddish) from tailward (bluish) flows, with green indicating regions of relatively low velocity flows.

For the NBz case of Figure 5, there is high latitude reconnection above the cusps, again indicated by the blue “x” markings in the figure. Reconnection is peeling off magnetotail plasma flux tubes and shedding them downstream. The convection flow pattern for the NBz case shows a complex transient system of eddy flows in the plasma sheet, parts of which feed the high latitude shedding of plasma. In addition, a much weaker double cell pattern is present in the inner magnetosphere.

Figure 5. The computed magnetohydrodynamic fields for the NBz case. (top) The magnetic (B) lines are indicated in the noon-midnight meridian. (bottom) The electric field is indicated as color contoured values of the Vx in the GSM-XY plane, coded to discriminate sunward (reddish) from tailward (bluish) flows, with green indicating regions of relatively low velocity flows.

Results

We begin by illustrating some trajectories that are typical of the entry of solar wind particles in our simulation. Trajectories typical of polar wind outflow have been previously published, e.g. by Delcourt et al. [1993, 1994], and are not much affected by the use of MHD fields, though the quantitative details may vary owing the detailed differences in the fields. The advantage of using MHD fields is that we can now consider the entry of solar wind through realistic boundary layer fields with reconnection operative. This allows us to more realistically assess solar wind entry, than was the case in Delcourt and Moore [1992], where we had to introduce solar wind particles inside the magnetopause or cusp and could not readily explore the LLBL as an entry region.

Figures 6 and 7 show examples for solar wind entry in southward and northward cases, respectively. These trajectories were selected with the criterion that they begin in the solar wind and subsequently enter a box of dimension +/- 6 Re GSM, centered on Earth, that is, the inner magnetosphere. These are the ions that gain substantial energies and become part of the ring current distribution. This can be seen from Figure 6 in which the proton begins by going along the dawn flank, but then slows and turns around at x ~ -16 Re, and travels back toward the Earth on the dawn side, entering into a conventional bouncing and drifting trajectory as it gains energy to the 100keV range from the convection electric field.

Figure 6. An example trajectory for solar wind entry in the SBz case.

Figure 7 for the NBz case differs from Figure 6 in ways that are typical of solar wind particles. First, entry is via the dayside cusp, where the proton penetrates quite deeply, and subsequently enters into the dawn LLBL flow, but on the inside of the magnetopause on closed flux tubes where it bounces up and down substantially in Zgsm. It eventually enters a trajectory that resembles the SBz case, but at substantially larger radius from the Earth, and with substantially lower energy, in the 10keV range.

Figure 7. An example trajectory for solar wind entry in the NBz case.

In Figure 8 we display for the SBz case, the plasma pressure in the GSM-XZ or noon-midnight meridian plane. Here the bow shock and magnetosheath are prominent features, as are the cusps and the cross section of the inner ring current-like region. Solar wind protons generally avoid the lobes and plasma sheet Earthward of -40 R_E, and it is unclear, in this view, how they are entering the inner magnetosphere to form the ring current-like structure, where pressure of these protons reaches about 1 nPa.

In the polar wind case, the polar outflow fills the lobes, much of it reaching the plasma sheet Earthward of about -40 Re and thence convecting back toward the Earth to form a region of drifting ring current-like protons that also has a pressure of < 0.1 nPa. Polar wind protons are also seen to convect to the magnetopause where they are jetted up over the poles, participating in the magnetosheath flow as they escape downstream.

Figure 8. For the SBz case, the plasma pressure is color contoured in the GSM-XZ or noon-midnight meridian plane. Solar wind particle pressures are shown in the upper frame; polar wind particle pressures are shown in the lower frame.

In Figure 9, we display, for the SBz case, the plasma pressure in the XY or ecliptic-equatorial plane, comparing the solar and polar wind distributions in the two panels. Features of interest for the solar wind include the realistic “painting” with particles of the bow shock and the magnetosheath, the low latitude boundary layer flows, and formation of a cavity in the wake region, within which few trajectories penetrate, while those that do have a relatively low associated pressure compared with the solar wind proper. This probably reflects a tendency for entering solar wind ions to be of relatively low energy. The figure clearly shows the principal path along which solar wind protons enter the inner magnetosphere, through the magnetopause along the dawn flank, forming a drifting ring current-like population, with a pressure reaching ~1 nPa. This feature is not as close to Earth as a full storm-time ring current, reflecting relatively weak inner magnetospheric return flow. This owes in part to the moderate SBz conditions for this simulation and in part to inherent limitations of MHD simulations of the inner magnetosphere.

The polar wind ions populate the plasma sheet, escaping downstream where they land beyond the convection reversal of Figure 5, and returning Earthward where they land within the Earthward flow. The latter illuminate a clear plasma sheet structure that connects directly with the inner magnetospheric closed drift region. Ionospheric plasma that is convected to the sunward reconnection region is forcefully launched into the magnetosheath flows along the low latitude flanks of the magnetosphere and downstream as part of the low latitude boundary layer.

Figure 9. For the SBz case, the plasma pressure is color contoured in the GSM-XY or equatorial plane. Solar wind particle pressures are shown in the upper frame while polar wind particle pressures are shown in the lower frame.

In Figure 10, we display for the SBz case the proton pressure in the last of the three cardinal planes, the GSM-YZ plane at X = 0. This cross section is dominated by solar wind and magnetosheath flows. The magnetospheric lobes are prominent in both solar wind and polar wind proton pressure, though for solar protons, they are profoundly empty, whereas for ionospheric protons, they are well populated but still have a relatively low pressure. The magnetosheath contains an enhancement of polar wind proton pressure, but it clearly does not compete with the solar wind pressure. In the solar wind case, a dawn-dusk asymmetry between the magnetosheath and the inner region hints at the dominant entry pattern into the inner magnetosphere via the dawn flank.

Figure 10. For the SBz case, the plasma pressure is color contoured in the GSM-YZ or dawn-dusk meridian plane. Solar wind particle pressures are shown in the upper frame while polar wind particle pressures are shown in the lower frame.

In Figure 11, we switch to the NBz case and display the plasma pressure in the XZ or noon-midnight meridian plane. The solar wind tail cavity still remains, but the lobes are no longer devoid of solar protons. Without lobes, the plasma sheet is hardly recognizable and is distributed all the way up into the polar caps, where it nearly meets a cusp that extends farther antisunward than in the SBz case. Sunward convection of plasma sheet material results from the action of high latitude reconnection, above the cusps, drawing the magnetotail plasmas into the lobes and polar cap, where plasma tubes are peeled off by high latitude reconnection..

The polar wind outflows for NBz similarly show no narrow plasma sheet feature. Escape occurs onto reconnected flux tubes shed downstream at high latitudes. The prominent magnetosheath jets of polar wind ions seen in the SBZ case are largely absent in this NBz case.

Figure 11. For the NBz case, the plasma pressure is color contoured in the GSM-XY or equatorial plane. Solar wind particle pressures are shown in the upper frame while polar wind particle pressures are shown in the lower frame.

In Figure 12, the pressure in the XY or equatorial plane is shown. For solar protons, it can be seen that the tail cavity of exclusion is considerably shorter and weaker than was the case for SBz. A dawn side region of entry still exists, but we know from looking at individual trajectories that entry begins in the cusp and passes through the dawn LLBL for NBz. The entry "plume" appears to extend across the plasma sheet diagonally in this case, rather than going mostly to the closed ring current-like region as it did for SBz. Apparently as a result, the ring current that forms is much more modest in pressure at < 0.1 nPa, and farther from Earth than for SBz. This result suggests a minimal solar contribution to the quiet NBz ring current.

The polar wind for NBz also has about the same pressure in the ring current region as for SBz (~3×10^{-2} nPa), but the pressure peaks farther from Earth than for SBz. Nevertheless, the polar wind protons are more extensive, extending closer to the Earth, and are comparable in pressure content to the solar protons in the ring current region, for NBz. There are plumes of ionospheric material flowing down each of the LLBLs, but a minimum of pressure in the center of the plasma sheet for NBz.

Figure 12. For the NBz case, the plasma pressure is color contoured in the GSM-XY or equatorial plane. Solar wind particles are shown in the upper frame while polar wind particles are shown in the lower frame.

In the final figure of this series, Figure 13, we display the corresponding NBz results for pressure in the YZ plane or dawn-dusk meridian. This plot complements the other cuts and shows that the plasma sheet sunward extension over the poles, meeting the cusps, is indeed localized in the noon-midnight meridian plane, forming a feature reminiscent of a Theta aurora. Simulations with finite By would likely shift this feature across the polar cap.

The polar wind pressure distribution in this plane shows a ring current-like feature. Owing to the very weak inner magnetosphere plasma flows, this feature forms farther from Earth than is ordinarily the case. Also, in this case there is little if any magnetosheath flow of polar wind protons, presumably because this plasma is being stripped off the polar regions by high latitude reconnection, instead of returning to the subsolar region and escaping into the magnetosheath upstream of X=0.

Figure 13. For the NBz case, the plasma pressure is color contoured in the GSM-YZ or dawn-dusk meridian plane. Solar wind particle pressure is shown in the upper frame while polar wind particle pressure is shown in the lower frame.

In Figure 14, we display an array of velocity distributions for the SBz case. In panel a), at X = 30 Re, Y = 0, we sample the velocities in six bins at 1 R_E resolution along Zgsm, spanning the neutral sheet. At this position the solar protons have insufficient numbers to evaluate, and we have about 100 polar wind protons per 1 R_E^3 bin. We find a cold narrow beam of polar wind protons at each extreme in Z. Both beams are traveling along the local magnetic field away from Earth and toward the current sheet at more negative Xgsm. As we step toward the current sheet from either side, a hot population appears, counterstreaming opposite to the cold antisunward flow. Many of these particles will subsequently convect through the inner magnetosphere and escape into the magnetosheath and downstream solar wind. Moving closer to the current sheet, the cold beam decreases in prominence, and the hot counterstreaming population increases in prominence and extent. Though we do not have a bin centered on the current sheet, such a bin would be symmetrically populated by an isotropic hot distribution of protons. This hot proton population is formed from the incoming cold polar wind beams during their encounter with the tightly curved current sheet fields, encountered as they travel from the lobes to the current sheet proper.

As the polar wind protons convect Earthward, they gain more energy, as seen in panel b) of the figure, representing a similar but longer cut through the thicker plasma sheet at X = -10, Y = 0, This location provides a good comparison with those presented earlier from the Polar/TIDE data obtained from a similar location of about 9.5 R_E at apogee. The sequence is qualitatively similar to that in the left panel, except that the mean energy of the protons is substantially higher following their earthward convection from more distant entry points, and the scale is more extended in Zgsm, reflecting the greater thickness of the current sheet at this distance. At this position, we have enough solar protons to show their velocity distribution in the right half of panel b). Here in the inner magnetosphere ring current region, solar particles entering via the dawn region contribute substantially to the particles present, with several tens per bin near the neutral sheet. It can be seen from the figure that the solar particles disappear more rapidly as we move away from the current sheet toward into the lobes, and as the polar wind protons turn to cold streams.

Velocity distributions for polar wind and solar wind protons are shown in the panel c) of Figure 14, at a point representative of the quiet ring current region just inside geosynchronous orbit near dusk. Here it can be seen that the solar protons are substantially more energetic than the polar wind protons. This appears to reflect their entry through the strongest part of the earthward convection for this growth phase period when the flank flows are stronger than the flows down the center of the midnight plasma sheet. It seems likely that a more active period with strong flow in the midnight plasma sheet would tend to reduce the difference between the mean energies attained by solar and polar wind protons in this region. Overall, these distributions of polar wind and solar wind protons bear a striking resemblance to the distributions attributed to those sources by Christon et al., [1994]. The polar wind protons have a soft energy distribution that declines with energy from low to high, while the solar wind protons have a distinct peak at 10's of keV. This can be seen from the inset energy distributions (integral over angles) shown in Figure 14. c).

Figure 14. Velocity distributions at selected locations for the SBz fields case: a) for polar wind particles only from $-2.5 \leq$ Zgsm ≤ 2.5 at Ygsm = 0 and Xgsm = -30 Re; b) for polar wind and solar wind particles from $-10<$ Zgms < 10 at Ygsm =0, Xgsm = -10 Re; c) for polar wind particles at Ygsm = 6 and Xgsm = Zgsm = 0; d) for solar wind particles at Ygsm=6, Xgsm = Zgsm = 0. Inset panels show the angle-integrated energy distribution of polar and solar wind protons. NOTE: the velocity scales vary from panel to panel in this figure.

Summary Discussion

We have previously suggested [Chappell et al., 1987; Delcourt et al., 1993; Moore and Delcourt, 1994] that much of the plasma sheet and ring current plasma may be provided by ionospheric sources, even though it is clear that the solar wind supplies the energy to power magnetospheric phenomena. Delcourt and Moore [1992] looked at solar wind entry and concluded that it was exceedingly difficult to get solar wind protons arriving via the dayside cusp region to reach the inner magnetosphere through the plasma sheet. We failed then to consider entry along the low latitude boundary layers near the flanks of the magnetosphere, but others have suggested or pointed out that entry path [Lennartsson, 1992; Richard, 2002, Walker, 2003, Peroomian, 2003, Winglee, 2003; Thomsen et al, 2003]. On the other hand, the polar wind does not seem to have been taken seriously as a source for the plasma sheet since Hill [1975]. Here we have taken a more comprehensive approach to solar wind entry than we did earlier, by initiating particles in the upstream solar wind and tracking them through a realistic interaction from MHD simulations. On the ionospheric side, we have ignored the O^+ in the magnetosphere for this study and have looked only at lighter ions that supply the plasma sheet and ring current regions. This will serve as a baseline for future studies considering the heavy ion component, originating mainly from auroral zone and cusp processes.

We have shown observations and simulations of magnetospheric ions and their structure in configuration space. We have also compared observations in velocity space for the region of the plasma sheet at two distances from Earth in the midnight plasma sheet and in the dusk quiet ring current region. We have considered two distinct sources of these ions in the solar wind and the polar wind, limiting the latter to the source that is essentially constant and pervasive at polar latitudes, and which creates the plasmasphere at lower latitudes. To explore the kinetic behaviors of the plasma ions, we treated them using single particle motions in global fields. The fields derive from snapshots of magnetohydrodynamic simulations and are therefore self-consistent in terms of bulk plasma and electrodynamic parameters, but frozen in time during the particle motions. No diffusive effects were included, but particles were introduced with randomized gyrophase. The fields are based only on a solar wind plasma source, revealing an implicit assumption that the ionospheric plasma does not alter the dynamics of the MHD simulation. Two extreme cases were considered: due northward and due southward IMF. This was not assumed to alter the upstream solar wind or polar wind boundary conditions. The magnetosphere was considered at equinox with no dipole tilt off normal to the Sun-Earth line. Several important results come out of this study: These limitations have been introduced to make this work practical. We believe them to have relatively minor impacts on the conclusions drawn from this work. below.

In agreement with results of others cited above, we find for SBz that the dawn low latitude boundary layer region is an effective source of solar wind particles to the ring current region. This route supplies the inner ring current region independent of any path through the midnight plasma sheet near the reconnection region. That region is much lower in solar proton density and pressure, compared with the dawn entry route, but is bathed thoroughly in polar wind outflows, which then flow into the ring current region along the traditional path. For the SBz conditions we studied, the solar wind contribution to the inner magnetospheric ring current region is dominant over the polar wind contribution in pressure and the two are comparable in density, with the solar wind energy distribution having a greater mean energy.

For NBz conditions, solar wind entry is through the cusp and then the LLBL, then again through the dawn flank. Owing to weak inner magnetospheric convection for this case, the dawn source region becomes much less effective at supplying the ring current region, and the polar wind source becomes comparable as a contribution to the weak NBz ring current. That the polar wind should make a stronger contribution at lower activity levels appears opposite to current expectations widely held in our community by both theorists and observers. However, those expectations are based upon O+ participation in the ring current, which we have not studied here.

Also for NBz, conditions, a feature resembling the “theta aurora” phenomenon appears in this simulation, largely in solar protons entering through the cusp and then making a circuit through the dawn LLBL into the plasma sheet and back up to the high latitude reconnection sites.

Figure 15 summarizes our results in a concise fashion using 3D cutaway diagrams. Because of the solar wind entry feature on the dawn flank we have focused here on the dawn side of the magnetosphere. Solar wind entry in the dawn LLBL convects immediately into the ring current region for SBz, short circuiting the midnight plasma sheet. Solar wind entry for NBz starts in the cusp, then into the dawn LLBL and diagonally across the inflated magnetotail, supplying some plasma back through the polar caps to the high latitude reconnection regions, but supplying little ring current. Polar wind outflow under SBz creates the plasma sheet and convects back into the ring current region. Polar wind escapes downstream for NBz, owing to high latitude reconnection, but also circulates to generate the inner part of the NBz ring current.

Figure 15. Summary plot showing Solar and Polar Wind magnetospheres for SBz and NBz. Each panel of these figures provides a cutaway of the pressure distribution for the corresponding case.

The current results should be considered in the context of the geopause suggested by Moore and Delcourt [1995]. It is apparent that solar wind protons enjoy a special access route to the inner magnetosphere that is quite different from that taken by ionospheric outflows (with the possible exception of such outflows into the dawn flank region). This leads to the creation of a “wormhole” that channels solar protons from the dawn low latitude boundary layer to the ring current region, producing considerable mixing of the two sources in the inner magnetosphere, for the conditions considered here.

Conclusions

Motivated by Polar/TIDE observations of the midnight plasma sheet region, we have investigated access to this region by solar wind and polar wind plasmas using single particle trajectory calculations in fields from a global magnetohydrodynamic simulation of SBz and NBz periods. This approach allows tracking of solar and polar wind contributions to magnetospheric plasmas, with the following main conclusions:

For SBz, solar wind enters along the dawn flank, and bifurcates into one component that continues down the dawn flank, and another component that convects immediately into the inner magnetosphere and into the ring current without passing through the midnight plasma sheet proper. Polar wind fills the plasma sheet proper and supplies a plasma pressure contribution that is appreciable but not dominant for the conditions we’ve studied in the ring current region. The density contributions of solar and polar wind protons are comparable, but the solar wind protons has a substantially higher mean energy. For NBz, solar entry is via the cusps, then into the LLBL entering along the dawn flank. The entering LLBL flow again bifurcates, with one component continuing along the dawn flank and the other proceeding diagonally across the plasma sheet and down tail, with a weak outer ring current contribution. The resultant solar wind ring current is much weaker and farther out from Earth than in the SBz case. Polar wind also enters the plasma sheet, which is distended in z and no longer shaped like a sheet. The polar wind bifurcates into one component that escapes downstream on reconnected field lines, and another that circulates into the ring current region and creates a weak but appreciable ring current, earthward of the weaker ring current formed by solar wind protons.

Simulated velocity distribution features in the SBz plasma sheet proper agree well with Polar observations of high Mach number lobal wind supply of the plasma sheet, with interpenetration of the polar wind streams from the two lobes and heating to form counterstreaming plasma sheet boundary layer populations and a hot isotropic central plasma sheet population. In the region observed by Polar, a hot solar wind proton distribution is found to occupy the current sheet region. These protons are on closed drift paths encircling the Earth for these conditions and may be considered part of the outer ring current. In the ring current region, the energy distributions of polar wind and solar wind protons agree very well with the results from AMPTE/CCE shown by Christon et al [1994] and support their identification of a soft component with polar wind origins, and an energetic peaked comonent with solar wind origins. This agreement supports the overall results of our simulation, showing that the principal observed features of the inner plasma sheet are formed naturally from a combination cold lobal wind outflows, combined with solar wind proton entry through the dawn flank region

We conclude that for typical conditions of moderate activity, magnetospheric transport of polar wind and solar wind ions is very different. Rather than following the polar wind through the lobes to the plasma sheet, the solar wind entry path is via the dawn flank and thence rather directly into the inner plasma sheet and ring current regions. As a consequence, the solar plasma ring current should be less affected by substorms and other magnetotail phenomena, though the polar wind or other ionospheric polar outflows would be expected to depend greatly on such processes. This type of behavior has been observed recently by Mitchell et al. [2003], who reported strong substorm modulation of Oxygen fluxes in the ring current, but with relatively little modulation of proton fluxes. We plan to return to this when we have completed a study contrasting auroral O^+ outflow behavior in the same fields we’ve used here to study polar wind protons.

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Figure Captions

See above

Running Title:

Plasma Sheet and Ring Current Formation